Obtaining cosmic ray propagation parameters from diffuse VHE γ-ray emission from the Galactic center ridge

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ABSTRACT

The recent discovery of diffuse, VHE γ radiation from the Galactic center ridge by the H.E.S.S. telescope allow for the first time the direct determination of parameters of galactic cosmic ray propagation models. In this paper we show that the diffuse γ-radiation near the Galactic center may be explained by the interaction of VHE cosmic ray (CR) protons with the interstellar gas located in several giant molecular clouds leading to a measurement of the cosmic ray diffusion coefficient for the galactic center region of $\kappa = 1.3$ kpc^{2}Myr^{-1} for a mean proton energy of ~ 3 TeV, if we assume that the CR protons originated from a supernova event (Sgr A East), which took off about 10 kyr ago. This value of κ is ~ 5 to 10 times smaller than the locally measured value.

Subject headings: diffuse emission, cosmic ray propagation, Galactic center

1. Introduction

The High Energy Stereoscopic System of four telescopes offers currently the best angular resolution for the study of VHE γ-rays from cosmic sources (Aharonian et al. 2006). With an angular resolution of $\sim 0.08°$, the H.E.S.S. Collaboration was able to resolve γ-rays associated with molecular clouds in the galactic center region (Aharonian et al. 2006): Whereas a relatively good correlation was found between the γ-ray and CS (with the latter measured by Tsuboi et al. (1999)) surface brightness distributions within 150 pc ($\ell \sim \pm 1°$ along galactic longitude) from the galactic center, this correlation degraded at a distance of 200

pc from the galactic center (i.e. at $\ell \sim 1.5°$). A strong indicator that this diffuse component is indirectly associated with a source at the galactic center is the similarity of the spectral indices of the point source HESS J1745-290 at the center and this newly discovered diffuse extended emission. Furthermore, the relatively good correlation within $\ell \sim \pm 1°$, but with degrading correlation beyond that, suggests that we are dealing with a source (e.g. the SNR Sgr A East or the central Black Hole Sgr A*) at the GC, which was active for some time in the past and that we are now seeing the high energetic particles diffusing from this central source (Aharonian et al. 2006). The most likely primary species responsible for the gamma-ray emission is then protons, since electrons would have to compete against synchrotron losses, resulting in a spectral steepening towards large distances. Apart from slight effects of energy dependent diffusion, protons, in a good approximation, do not loose energy within this environment, resulting in an approximate invariant spectral index with distance.

Whereas these results are important from an Astrophysical viewpoint, it is also of importance from a cosmic ray viewpoint, i.e. the study of cosmic ray propagation in our galaxy: Aharonian et al. (2006) suggested that the diffusion coefficient for protons in the 4 to 40 TeV range should be less than 10^{30} cm^{2}s^{-1} (or 3.5 kpc^{2}Myr^{-1}) as a result of enhanced turbulence and higher magnetic field strengths in the GC region. The H.E.S.S. data therefore offer a unique possibility to measure the diffusion coefficient in this part of the galaxy and to compare with other measurements of the galactic diffusion coefficient. This is in particular important as it has been shown (Büsching et al. 2005) that, given SNR are the main sources of CR, the widely used method to obtain propagation parameters by fitting secondary to primary data is at least tainted, as the CR primary component then shows strong variations in space and time.

In this paper we will model a transient source at the GC with an activity time-scale in the past. By solving the transport equation for proton propagation along the galactic plane, we will obtain the range of diffusion coefficients, which fit the observed HESS profile best. To do this we will also model the gas distribution as traced by the CS emission.

Tsuboi et al. (1999) was the first to obtain a full coverage of the Galactic Center Bow (GCB) and the molecular cloud structures in CS in the region of interest. Since the gamma-ray surface brightness is reflected by the line-of-sight integral of the product of the cosmic ray and gas densities, we will introduce 3D structures in the GC region (even though not strictly modelling the GCB itself), such that the line-of-sight integral through these model structures reproduce the true line-of-sight integrals through the gas density within $\sim 5\%$ accuracy, as described in more detail below.

Using the diffusive model of CR propagation, together with observations made by the High Energy Stereoscopic System (H.E.S.S.) (Aharonian et al. 2006) it is possible to get an

estimation of the diffusion coefficient controlling cosmic ray (CR) transport in the galactic center region.

1.1. γ-rays from pion decay

The omnidirectional (i.e. integrated over solid angle) differential γ-ray source function $q_{\pi^0}(E_\gamma, \vec{r})$ at the position $\vec{r} = (l, b, r)$ for the decay $\pi^0 \rightarrow 2\gamma$ is given by (Büsching et al. 2001)

$$q_{\pi^0}(E_\gamma, \vec{r}) \;=\; 2\int_\eta^\infty \frac{Q_{\pi^0}(\gamma_\pi, \vec{r})}{\sqrt{\gamma_\pi^2 - 1}} d\gamma_\pi \tag{1}$$

where γ_π is the pion Lorentz factor. The lower boundary of the integration is given by

$$\eta \;=\; \frac{E_\gamma}{m_\pi c^2} + \frac{m_\pi c^2}{4\,E_\gamma}. \tag{2}$$

The pion source function then is

$$Q_{\pi^0}(\gamma_\pi, \vec{r}) \;=\; \rho_{\rm gas}(\vec{r})\, c \int_{\gamma_{\rm thr}}^\infty \beta\sigma_{pp}^{\pi^0}(\gamma_p, \gamma_{\pi^0}) N_p(\gamma_p, \vec{r}) d\gamma_p \tag{3}$$

where $\sigma_{pp}^{\pi^0}$ is the total cross section for pion production in pp collisions and N_p the CR proton spectrum. The differential photon flux from the decay of CR induced π^0s from the direction (l, b) is given by integrating Eq.1 along the line of sight

$$\frac{dN(E_\gamma, l, b)}{dt\, dE_\gamma\, d\Omega} \;=\; \frac{1}{4\pi}\int q_{\pi^0}(E_\gamma, \vec{r}) dr \tag{4}$$

The above calculation is for pion production from pp interactions only. The effect of the known chemical composition of the ISM can be taken into account by increasing the total pion production cross section by a factor of 1.30 (Mannheim & Schlickeiser 1994).

2. Reproducing the diffusive γ-ray emission from the Galactic center

For our studies we reproduce the diffusive γ-ray emission calculating the line of sight integral Eq. 3 for various (l, b) combinations. As we are only interested in relative intensities, we can use instead of Eq. 3 the relative emissivity

$$\epsilon(l, b) \;\propto\; \int_{r=0}^\infty \rho(l, b, r) N_{CR}(l, b, r)\, dr \tag{5}$$

where $\rho(l, b, r)$ is the target material density as a function of galactic coordinates and $N_{CR}(l, b, r)$ is the calculated CR density at the point defined by triplet (l, b, r).

2.1. Gas distribution near the Galactic center

The inner ±150 pc region of the Galaxy contain interstellar H_2 gas of about 2 to $5{\times}10^7$ solar masses (Tsuboi et al. 1999) in a rather complex setup of molecular clouds. For our analysis we assumed that the target material density function can be adequately described by the superposition of five spherical Gaussian functions upon an asymmetric Gaussian base. These functions represent the molecular clouds associated with the radio arc of Sgr A, Sgr B, as well as the longitude varying line-of-sight projection effect of the "Galactic Center Bow" as described by Tsuboi et al. (1999). Even though we are able to reproduce the observed line-of-sight gas densities within about 5% from the observed values, uncertainties in the exact depth distribution along the r-coordinate in Eq. 5, is expected to result in a $\sim$ 50% systematic uncertainty in the final estimate of the diffusion coefficient.

2.2. Cosmic ray distribution near the Galactic center

The CR distribution as a function of spatial coordinates is calculated using the diffusive model of CR propagation. We calculate the CR density assuming the CR coming from a single SNR event 10 kyr ago, accelerating particles for a certain time. As was pointed out by Maeda et al. (2002), the SNR Sgr A East has an estimated age of 10 kyr, but also younger ages have been given for that SNR (Rockefeller 2005). For our study, we assume that Sgr A East has an age of 10 kyr and was accelerating CR on various timescales less than 10 kyr. We are interested in the CR distribution near the source and thus neglect the effects of spatial inhomogeneities in the interstellar gas density (which are small for CR protons with the energies we are dealing with) by assuming a mean gas density, and also boundary effects by imposing boundary conditions for the CR propagation problem at infinity. In this case one can find a solution for the propagation equation in the literature (Syrovatskii 1959). Using the integral in Eq. 5 the emission seen by H.E.S.S. (Aharonian et al. 2006) can be recreated for different diffusion coefficients as shown in Fig. 1 (top). As noted by Aharonian et al. (2006), the excess counts observed by H.E.S.S. follow the known target material density fairly well, except for the region $l \geq 1°$. This provides a gauge for approximating the diffusion coefficient governing the CR propagation near the galactic center.

To obtain better counting statistics, we compare the model and observed H.E.S.S. excess counts, integrated over Galactic latitude. The excess counts observed by H.E.S.S. then are proportional to the integral

$$\epsilon(l) \quad \propto \quad \int_{r=0}^{\infty} \int_{b=-\pi 2}^{\pi/2} \rho(l,b,r) N_{CR}(l,b,r) r \, db \, dr, \tag{6}$$

where the CR density N_{CR} has been calculated for different diffusion coefficients, as shown in Fig. 1 (bottom). The obtained fit is normalised to the total numbers of excess counts before calculating the corresponding χ^2 value. The results of the analysis are shown in Fig. 2 below. The optimal value for the diffusion coefficient k was found to be

$$\kappa = 1.3\,\mathrm{kpc}^2\mathrm{Myr}^{-1}, \tag{7}$$

which is about 40% smaller than the diffusion coefficient estimated by Aharonian et al. (2006). We also note that the minimum reduced χ^2 is 1.5 (for ~ 25 d.o.f.), which indicates that the data are marginally described by the model. Note that we do observe a well-defined minimum in Fig. 2, leading to the abovementioned measurement of κ. It would be interesting to see if more sophisticated 3D modelling of the total gas distribution result in even smaller χ^2 values. Because of this uncertainty, we estimate a systematic uncertainty of $\sim 50\%$ on the measured value of κ.

2.3. Mean CR energy

In the last section, we have shown that the diffuse γ-ray emission from the Galcatic center ridge can be explained by CR hadrons which propagation can be described by a diffusion coefficient of $1.3\,\mathrm{kpc}^2\mathrm{Myr}^{-1}$. This diffusion coefficient is valid for CR generating the bulk of the γ-ray emission in the H.E.S.S. energy range.

To compare this value with that obtained by fitting local CR data, as derived e.g. by Moskalenko et al. (2002), Jones et al. (2001) or Maurin et al. (2002), we have to estimate the energy of the CR probed here. For this investigation, we approximate the sensitivity of the H.E.S.S. telescope array by a box function from 0.4 TeV to 20 TeV. For the CR proton spectrum we assumed a power law with the observed photon index $\Gamma = 2.29 \pm 0.27$ (Aharonian et al. 2006). We used the Pythia (Sjöstrand et al. 2001a,b) event generator package to calculate the number of γ-rays with $E_\gamma > 0.4\,\mathrm{TeV}$, for different CR proton energies. The result of this calculation is shown in Fig. 3. The maximum number of photons is produced by CR protons with energies of about 2.2 TeV, given a proton spectral index of 2.29. Note that the location of the maximum depends on the proton spectral index. Given the uncertainties stated by Aharonian et al. (2006), we find that CR protons with energies in the range 1.7 TeV to 3 TeV contribute mostly to the γ-rays seen by H.E.S.S. Assuming a diffusion coefficient of the form

$$\kappa \;=\; \kappa_0 \left(\frac{\xi}{\xi_0}\right)^{0.6}, \tag{8}$$

where $\xi_0 = 1\,\mathrm{GV}$ and ξ the particle rigidity we find $\kappa_0 = 0.013\,\mathrm{kpc}^2\mathrm{Myr}^{-2}$, which is significantly smaller than the values found by fitting local CR data. However, κ for the latter

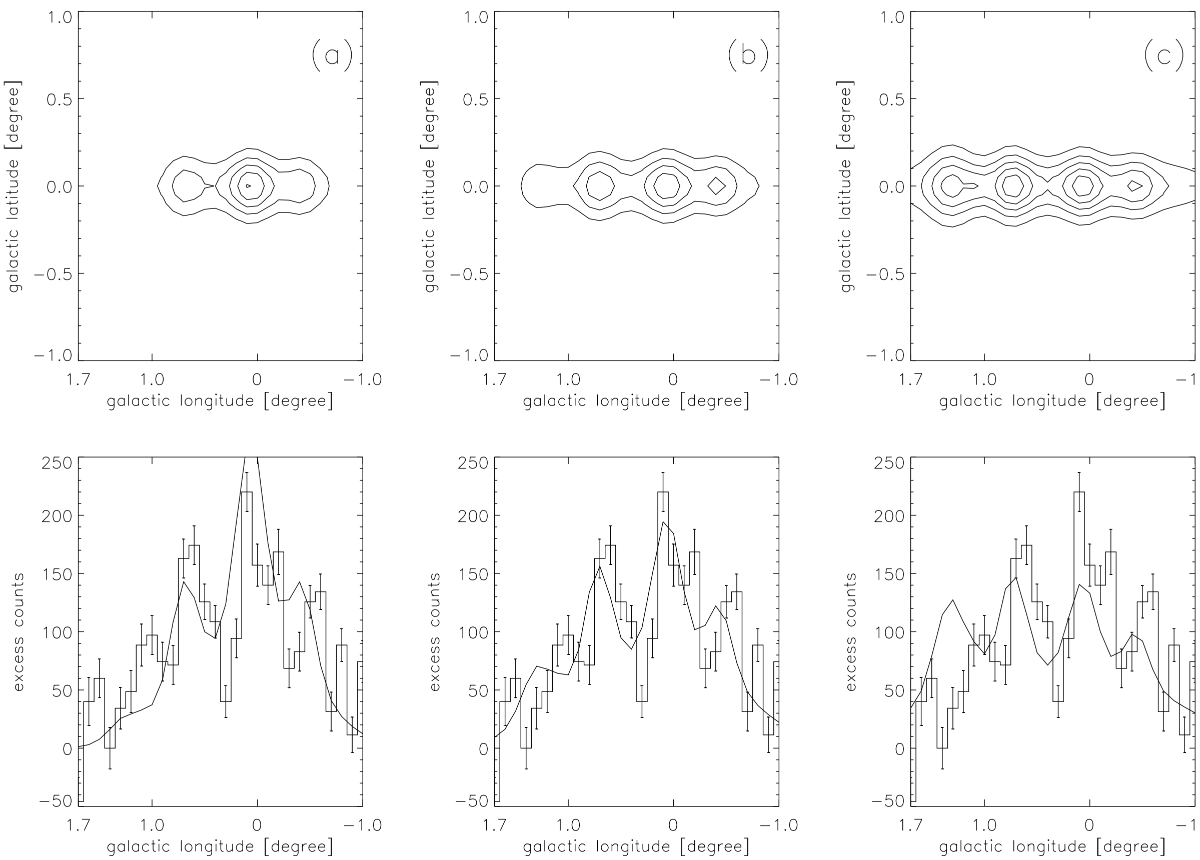

Fig. 1.— Calculated emission sky maps (top) together with the calculated excess counts (bottom) shown as the solid lines. The histogram indicate the excess counts from the H.E.S.S. observation (Aharonian et al. 2006). The figures (a), (b) and (c) where generated for diffusion coefficients with values 0.3 $kpc^2 Myr^{-1}$, 1.3 $kpc^2 Myr^{-1}$ (best fit) and 15.1 $kpc^2 Myr^{-1}$ respectively.

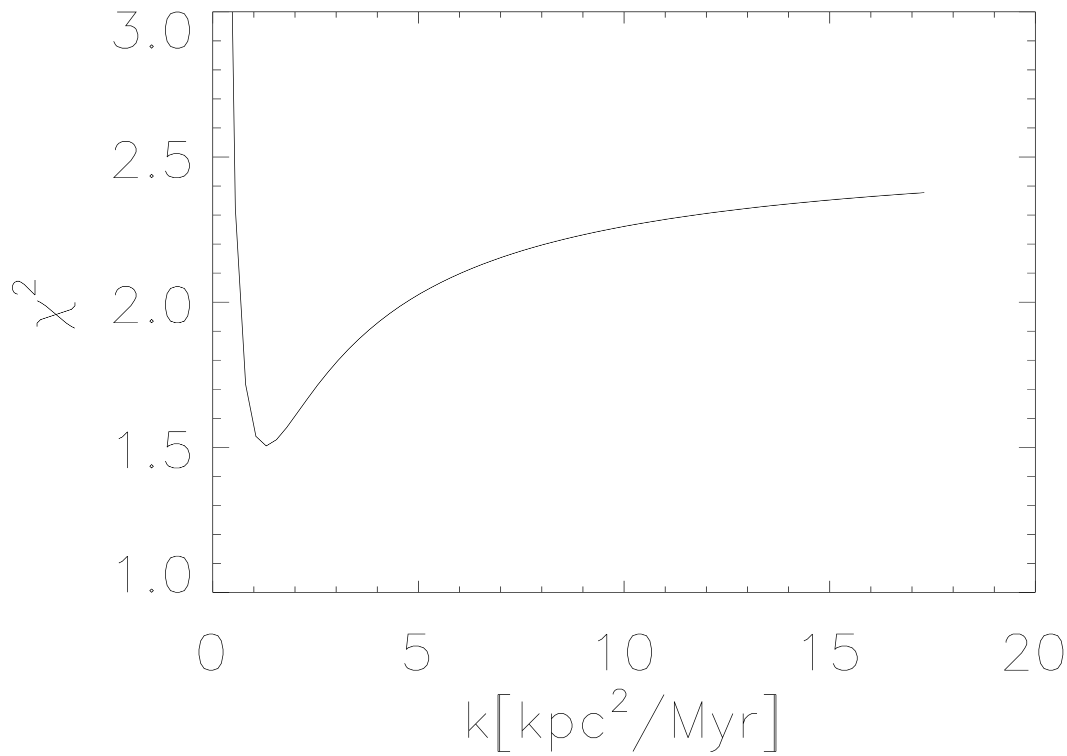

Fig. 2.— Reduced χ^2 values plotted for different diffusion coefficients. We find a well defined minimum for a diffusion coefficient of $k = 1.3\ kpc^2 Myr^{-1}$.

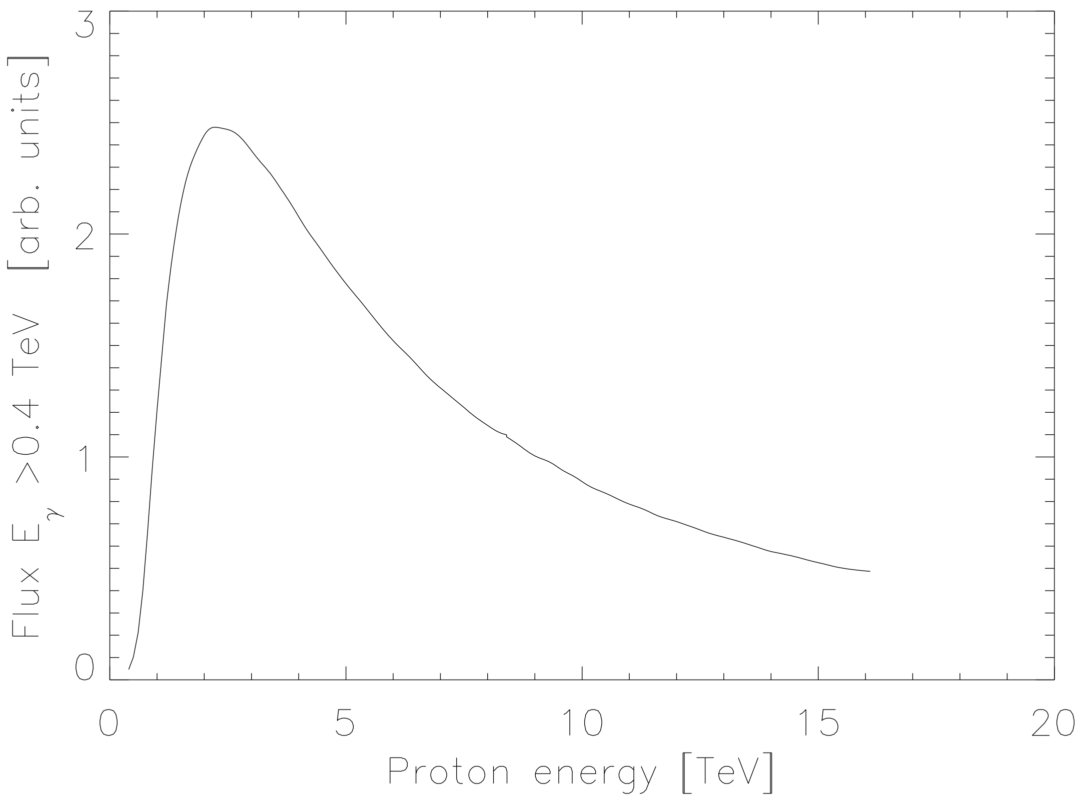

Fig. 3.— Number of photons with $E_\gamma > 400\,GeV$ for different CR proton energies assuming a CR proton spectral index of $s\,=\,2.29$.

range from $0.0535\,\mathrm{kpc}^2\mathrm{Myr}^{-2}$ to $0.201\,\mathrm{kpc}^2\mathrm{Myr}^{-2}$, as compiled by Maurin et al. (2002) (with references therein). This finding can be well explained by enhanced turbulence and a higher field strength of the interstellar magnetic field in the Galactic center region. We note however that the rigidity dependence of 0.6 can only apply to a limited energy (rigidity) range, since κ must always be larger than the Bohm limit.

3. Summary and Discussion

We have shown that the progress in the imaging Cherenkov technique now makes it possible for the first time to measure the CR diffusion coefficient in other parts of the Galaxy. A diffusion coefficient of $\kappa \sim 1.3$ $\mathrm{kpc}^2\mathrm{Myr}^{-1}$ appears to be well measured from the data, although we have to add a $\sim 50\%$ systematic undertainty arising from uncertainties in the actual 3D gas density distribution, as well as uncertainties on the epoch when the central source activity started, which was assumed to be 10 kyr in this paper. The most likely central source is Sgr A East, for which the epoch of onset of activity is ~ 10 kyr, but if the central source was the central massive black hole Sgr A*, the timescale of activity would be much less certain, resulting in even larger uncertainties on κ. Note however that, given an initial epoch of onset of activity (i.e. 10 kyr), estimates of κ appear to be fortunately robust against uncertainties in the detailed time profile of particle acceleration within 5 kyr after the SN explosion. For example, reducing the "on"-time of the source by a factor of five, decreases the diffusion coefficient by 40%. Such detailed studies will however be treated in a subsequent paper. Thus, if Sgr A East was the source of CR, then we have a relatively accurate masurement of κ.

In general, following the notion of Aharonian et al. (2006) to constrain the cosmic ray diffusion coefficient κ from the spatial distribution of diffuse γ-rays resulting from impulsive injection of a CR source at some time in the past, we have shown that one can obtain unique measurements of the diffusion coefficient, provided that the gas density distribution, as well as the epoch of onset of central source activity is known. We also showed that the CR diffusion coefficient in the Galactic center region is significantly smaller than that obtained by fitting local CR data. Our understanding of turbulence theory is however still too limited to understand how diffusion coefficients scale with the turbulence δB, the correlation length associated with this turbulence, the total magnetic field strength B and rigidity dependence for perpendicular and parallel diffusion. Hopefully our new measurement of κ will help to constrain results from turbulence theory.

REFERENCES

Aharonian et al. 2006, Nature, 439,695

Büsching I., et al., 2005, ApJ, 619, 314

Büsching I., Pohl M., Schlickeiser R. 2001, A&A, 377, 1056

Jones, F. C., Lukasiak, A., Ptuskin, V., & Webber, W. 2001, ApJ, 547, 2644

Maeda, Y., et al. 2002, ApJ, 570, 671

Mannheim, K., & Schlickeiser, R. 1994, A&A, 286, 983

Maurin, D., Taillet, R., & Donato, F. 2002, A&A, 394, 1039

Moskalenko, I. V., Strong, A. W., Ormes, J. F., & Potgieter, M. S. 2002, ApJ, 565, 280

Rockefeller, G., et al., 2005, submitted to ApJ(astro-ph/0506244)

Sjostrand, T., Lonnblad, L., & Mrenna, S. 2001a, Pythia 6.2: Physics and Manual (hep-ph/0108264)

Sjöstrand, T.,et al., 2001b, Computer Physics Commun. 135, 238,

Syrovatskii, S.I., 1959, Sov. Astron., 3, 22

Tsuboi, K., Toshihiro, H., & Ukita, N. 1999, ApJS, 120, 1